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EMERGING NEEDS FOR MOBILE NUCLEAR POWERPLANTS

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ABSTRACT

This report examines the incentives for broadening the present role of civilian nuclear power to include mobile nuclear powerplants that are compact, lightweight, and safe. Specifically, this report discusses the incentives resulting from the growing importance of (1) a new international cargo transportation capability and (2) the capability for development of resources in previously remote regions of the earth including the oceans and the Arctic. This report surveys present and potential systems (vehicles, remote stations, and machines) that would both provide these capabilities and require enough power to justify using mobile nuclear reactor powerplants.

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SUMMARY

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This report examines the incentives for broadening the present role of civilian nuclear power to include mobile nuclear powerplants that are compact, lightweight, and safe. Specifically, this report discusses the incentives resulting from the growing importance of (1) a new international cargo transportation capability and (2) the capability for development of resources in previously remote regions of the earth including the oceans and the Arctic. This report surveys present and potential systems (vehicles, remote stations, and machines) that would both provide these capabilities and require enough power to justify using mobile nuclear reactor powerplants.

The systems discussed include vehicles for international cargo transportation (ships, submarines, air cushion vehicles (ACVs), airships, and aircraft), submersibles for underwater prospecting, research, construction, mining, farming and ranching, habitats and energy depots (small central power stations) under the oceans and in the Arctic, machines for underwater mining and underground tunneling. The reactor thermal powers that would be needed range from under 0.1 megawatt for small work submersibles and small habitats to several megawatts for research submarines, tunneling machines, and large habitats to hundreds of megawatts for ships, submarines, ACVs, and deep underwater shaft mining to thousands of megawatts for very large aircraft and ACVs.

INTRODUCTION

A broadening role for civilian nuclear power has been indicated by recent developments. First, for land-based electric generating plants

nuclear fuel is becoming increasingly competitive with fossil fuel as shown by the increasing number of operating and planned nuclear plants (see also ref. 1). Second, there is an awakening multi-country interest in the potential economy of nuclear ships, highlighted by the U. S. Maritime Administration's Marine Nuclear Propulsion Program (refs. 1 and 3) and by the projection of the Japan Atomic Industrial Forum that there will be 280 nuclear containerships by the year 2000 (ref. 4).

This report examines the incentives for further broadening this role to include mobile nuclear powerplants that are compact, lightweight, and safe. Specifically, this report discusses the incentives resulting from the growing importance of (1) a new international cargo transportation capability and (2) the capability for development of resources in previously remote regions of the earth including the oceans and the Arctic. This report surveys present and potential systems (vehicles, remote stations, and machines) that would both provide these capabilities and require enough power to justify using mobile nuclear reactor powerplants.

Of course, the likelihood of a broadened role for mobile nuclear reactor powerplants will depend on more than just a need for their capabilities. There are questions of technical and economic feasibility; and in answer to these questions the indications of feasibility of mobile nuclear reactor powerplants (hereafter referred to as MNPs) have been outlined in a companion study (ref. 5).

Briefly, from Ref. 5: Marine nuclear powerplants (mainly pressurized water reactors) seem clearly technically feasible for widespread application to merchant shipping. The technology for more advanced MNPs (compact and lightweight) for undersea use could come from several sources: (1) advanced marine reactor systems under development for merchant ships (refs. 2, 3, 6 and 7), (2) low-critical-mass studies at Los Alamos (refs. 8 and 9), and (3) the U. S. A. E. C. SNAP (Systems for Nuclear Auxiliary Power) programs.

As for airborne use it is not yet clear what the best reactor concept is. This situation contrasts to the established prevalence of

one reactor type (pressurized water) for present and planned marine use. However, civilian studies of reactors for aircraft have tended to favor the gas-cooled reactor concept with liquid metal cooling being the next choice (refs. 10 to 13). The technology for these reactors could also come from several sources: (1) high-temperature, gas-cooled, land-based power reactors which entered the commercial market in 1971 (ref. 14), (2) advanced space nuclear power systems, some of which are outgrowths of SNAP programs (refs. 15 and 16), and (3) technical feasibility studies of airborne nuclear reactors (refs. 17 to 21).

The indicators of commercial feasibility for land-based power reactor and present marine reactors were mentioned in the first paragraph of this introduction (see refs. 1 to 4). Furthermore, cost studies of conceptual airborne vehicles (air cushion vehicles and aircraft) powered by conceptual nuclear powerplants also indicate an economic advantage of nuclear over chemical fuel (refs. 23 and 23).

An examination of the potential applications for MNPs can serve three major purposes: (1) to identify the broad range of socially-derived needs toward which MNP research and development could apply, (2) to identify the potential importance of an advanced powerplant technology in terms of capability and diversity of applications, and (3) to become a key part of any later assessment of the total impact of this technology.

WHY DEVELOP NUCLEAR POWERPLANTS FOR MOBILE APPLICATIONS?

Inherently a nuclear reactor is heavy and bulky largely because of the biological shield and safety systems. What incentive is there to consider tackling the two formidable problems of developing a nuclear reactor that is compact and light enough to be mobile and safe enough to withstand potential impacts? A quick answer is energy density. One pound of uranium has the energy equivalent of about 1.9 million pounds of oil (about 6000 barrels).

Because of its energy density nuclear fuel provides an energy autonomy which in turn provides: (1) nearly unlimited vehicle range without refueling, (2) a large "revenue-cargo" volume (which would have been taken up by chemical fuel) as the vehicle energy requirements get larger, (3) surface and weather-independence for undersea applications, and (4) energy independence and reserve endurance in remote areas. Thus the high energy density of nuclear fuel could offer distinct advantages in performance, convenience, and cost to the owner and operator of a nuclear-powered vehicle.

Nuclear powerplants can also be used for purposes other than generating electricity or thrust. For example, the radiation, the constant fuel weight, or the direct use of the reactor heat can be important for some applications.

Beyond these user benefits are a number of national benefits that could be derived from the development and widespread use of MNPs. Some of these national benefits are described below and all subsections except "Energy Consumption" are based on a description of the Nuclear Propulsion Program of the U. S. Maritime Administration (MARAD) (ref. 3). Each subsection describes the national benefits of nuclear propulsion for merchant ships and then generalizes for other applications.

Superior Economic Performance - Cost savings from using nuclear propulsion in merchant ships may be used to decrease freight rates and/or increase profit to the ship operator, making possible a reduction or elimination of the annual federal ship operating subsidy (ref. 3). Nuclear power potentially offers cost reductions in aircraft (ref. 23) and cost competitiveness for new cargo vehicles such as submarines (ref. 24) or air cushion vehicles (ACVs) (ref. 22). These competitive cost, higher speed vehicles would open new trade routes and attract new categories of cargo (refs. 24-28).

In particular, the speed, low cost, and mobility of the ACV freighter make it well suited to expand old markets and create new ones (ref. 27). In a roll on/roll off mode the ACV freighter could carry cars, trailer trucks, tractors, or mobile homes to places that could never be reached

by ships. On transocean routes it could carry large preloaded pallets of machinery and appliances at a speed that would allow expensive inventories of imported goods to be reduced. And it could carry large quantities of bulky and heavy perishables, including fresh foods, highly competitive products, and short-lived chemical compounds.

Stimulus to U. S. Industry - Successful development of nuclear propulsion for merchant ships has significant potential for strengthening the U. S. shipbuilding industry and hence for stabilizing employment in that industry and in related equipment supply industries, and for strengthening the competitive position of the U. S. merchant fleet (ref. 3). In addition to the industries for their own manufacture, both MNPs and the various systems that would use them would be principal features of new industries dedicated to oceanic and Arctic resource development, international cargo transportation, and remote power supply.

Improved Balance of Payments - Use of nuclear propulsion for merchant ships will provide a major savings in foreign fuel purchases. From MARAD data in Ref. 29, one oil-fired ship of 120 000 shaft horsepower (shp) will burn at least \$100 million worth of fuel oil in its lifetime of 25 years. This fossil fuel is obtained almost entirely from foreign sources (ref. 3). Penetration of a worldwide market for mobile nuclear power systems and instruments would provide substantial foreign sales opportunities.

Improved National Capabilities - Development of nuclear powerplants for merchant ships will provide (1) technology and experience applicable to small (100-500 kWe) land-based nuclear electric generating plants, (2) reduction of the potential for international pressures related to foreign fuel supplies because of decreased dependence on fossil fuel, and (c) economic operation of higher speed tankers having larger capacity (because only emergency fuel oil need be carried) to deliver more fuel faster and cheaper to domestic users.

Development of compact lightweight reactors for undersea application would allow the U. S. to become more self-sufficient in important minerals. Development of large nuclear-powered ACVs with their unusual

mobility would permit all-season operation throughout the Arctic and provide a new geographic freedom in locating trade centers and ports (ref. 27). Large ACV freighters and associated hoverports could offer two possible solutions to the problem of urban congestion. First, a hoverport could serve as a relief valve for existing cities by shifting business centers outside them. Second, a hoverport could offer an economic base for totally new cities, able to absorb new populations.

Energy Consumption - Because fossil fuels are nonrenewable resources and are being rapidly depleted, it is becoming increasingly important that we reduce our dependence on them.

The widespread use of nuclear fuel in marine transport alone would substantially ease the demand for our diminishing supply of petroleum. The magnitude of the potential petroleum savings is illustrated by the following exercise:

From MARAD data mentioned earlier, an oil-fired ship of 120 000 shp will burn a minimum of \$100 million worth of fuel oil in its lifetime (about 25 years). The most common fuel oil is bunker "C" which now costs about \$4 per barrel. Thus at this price during its lifetime a 100 000 shp ship will burn about 20 million barrels of fuel oil.

If all 500 ships with 100 000 or greater shp that are needed by 1990 (MARAD study, refs. 2, 3, and 29) (fig. 1) are oil fired they will consume 10 billion barrels of fuel oil during their lifetimes. Assuming that one barrel of crude oil produces one barrel of refined fuel oil, these 500 ships during their lifetimes will consume all of the oil from Alaska's North Slope (using the widely quoted but probably conservative reserve figure of 10 billion barrels).

USES FOR MOBILE NUCLEAR POWERPLANTS

The major uses of mobile nuclear reactor powerplants (MNPs) may be categorized as (1) international cargo transportation, (2) resource development, and (3) remote power supply. For each category, this section discusses the need for the potential of various systems

whose power needs could be satisfied by MNPs. Because of different amounts of information available, the discussion of the various systems necessarily varies in detail. To aid comparisons of power needs, all powers (horsepower and electrical power) obtained from the references are converted to reactor thermal power assuming an efficiency of 30 percent, unless otherwise specified.

Cargo Transportation

During the past two decades a world economy highly dependent on international trade has developed. The growth in both population and in the volume of world trade (fig. 2) has brought about a parallel and dramatic growth in ship sizes and propulsion power levels. Figure 3 shows the growth of dry bulk carriers. Tankers have had similar increases in ships' sizes and the speed of cargo liners has increased by more than 50 percent in the last five years (ref. 2). The growth of trade and ship size and speed is expected to continue. Such a continuing requirement for larger, higher speed vehicles, and hence higher power levels, will increasingly favor nuclear powerplants for international cargo vehicles.

Ships

In competitive and growing markets involving product transportation there is obviously a premium on speed. The next generation of container ships will carry transoceanic cargo at twice the speed (and the same cost) of most existing ships. The price level is held by relying on the "economy of size" whereby a larger vehicle with its larger payload can usually carry cargo more cheaply per ton than a smaller vehicle with its smaller payload. However, both characteristics - the increased speed and size - require more power.

A study for MARAD (cited in refs. 2, 3, and 29) projects that in the year 1990 there will be a need for world wide shipping fleet of 500 ships over 100 000 shp and 2500 ships over 40 000 shp (fig. 1). MARAD economic studies have indicated that nuclear power for merchant shipping is presently economically competitive with oil-fired power above 100 000 shp (ref. 29). The studies also suggest that by 1978 nuclear power could be competitive at 40 000 shp and above.

Existing nuclear powered merchant ships are the Savannah (21 knots, 22 000 shp, 74 MWt reactor), the Otto Hahn (15 knots, 10 000 shp, 38 MWt reactor), and soon the Mutsu (16.5 knots, 10 000 shp, 36 MWt reactor) and the Enrico Fermi (22 000 shp, 80 MWt reactor) (ref. 30). The next generation of container ships will be represented by 33 knot, 120 000 shp vessels. Eight of these ships (all oil fueled) have been ordered by Sea-Land Service, Inc.; the first was to be delivered in August 1972.

As for tankers they "do not have the same requirement for high speeds (as container ships), and so even 250 000 ton tankers rarely need shaft horsepowers greater than 35 000. . . However, a tanker of 400-500 000 tons is on order in Japan and tankers of this size would need 60-70 000 shp." (ref. 30).

But there is one situation where high speeds for tankers might be desirable and hence where higher power might be needed. This situation is outlined in Ref. 2; most of the remainder of this paragraph is excerpted from that reference. Usually comparison are made one-for-one, that is, a nuclear fueled ship of a given size is compared to a fossil fueled ship of the same size and service. Another approach is to compare several high-speed nuclear ships with a larger nuclear of slower-speed fossil ships (table I). Historically, tankers travel at 15-16 knots because of economics. At this speed tankers use anywhere from 3-10 percent of their payload as fuel for propulsion. Any significant speed increase would require a substantial power increase (power increases as the cube of the speed) and would seriously reduce the tanker's payload capacity. At twenty five knots, 40 percent of the payload capacity could be required for ship propulsion purposes. For a nuclear tanker of 120 000 shp, the nuclear powerplant would take up less volume than two 60 000 shp fossil boilers and would not require any fuel volume. Thus five nuclear tankers traveling at 24 knots could do the job of eight fossil tankers traveling at 15.5 knots. The capital cost of the five nuclear tankers would be about the same or less than the eight fossil tankers, and the annual fuel savings might be \$5-6 million for the nuclear ships.

The power needed for large fast container ships will range between 80 000 and 150 000 shp for cargo deadweights between 20 000 and 40 000 tons and speeds between 25 and 33 knots (ref. 30). The reactor power will range from 200 to 380 MWt. The power needed for large oil tankers (with 16 knot speed) will range from 35 000 shp for a 250 000 deadweight ton (dwt) capacity to 70 000 shp for a 400 000 to 500 000 dwt capacity. These shaft powers will require a reactor thermal power output of 90-180 MWt (ref. 30). For large tankers (250 000 dwt) with higher speeds (24 knots) the power requirements will be about 120 000 shp or 300 MWt reactor power (ref. 2).

Submarines

At higher speeds (above 20-30 knots depending on the vessel size) and in rough seas, submarines are more efficient than surface ships because they do not create waves underwater. But submarines are generally more expensive to build than surface ships. Thus unless there are geographic or topographic restrictions to surface ships, submarines are not competitive with them (ref. 24).

One region where surface ships are severely restricted is the Arctic. Most of the studies of commercial nuclear submarines have been directed toward their use as Arctic crude oil tankers for transporting oil to North Atlantic ports (ref. 24, for example). By loading and transporting the oil underwater the submarines could avoid the hostile surface in the Arctic. There is the further possibility that a nuclear cargo submarine could make complete East-West Arctic crossings thus opening the long-sought commercial Northwest Passage. Although a precedent for this was set in 1958 when the nuclear submarine Nautilus crossed under the North Pole, the present maritime Law of the Sea could be invoked to prevent passage of submerged cargo carriers through the ice-covered Bering Strait (ref. 25).

The power needed for large submarines (for containerized cargo) would range from 27 400 shp (42 000 metric ton displacement, 20 knots) to 218 000 shp (104 000 metric ton displacement, 37.4 knots) (ref. 31). The corresponding reactor powers would be 70 to 560 MWt. From Ref. 24, a 75 000 shp Arctic oil submarine tanker powered by a 250 MWt

reactor could have either a cargo deadweight of 170 000 metric tons and a speed of 19 knots or a cargo deadweight of 250 000 metric tons and a speed of 17 knots.

Air Cushion Vehicles (ACVs)

The ACV provides a step increase in surface mobility over present vehicles. It needs no surface contact; it glides on a cushion of air over water, ice, snow, mud, sand or any relatively flat surface. The ACV is a relatively new vehicle. In 15 years it has gone from "table-top" demonstration to commercial vehicles carrying more than a million passengers each year. By the end of the century its mobility and speed could dramatically affect world trade and the distribution of people on the earth (ref. 27).

Small ACVs up to about 200 tons have been used all over the world for ferry service, coastal patrol, river exploration and equipment transport for Arctic oil fields. Much of the operating experience of the larger ACVs has come from the SR N4 (fig. 4) (ref. 32) which has provided English Channel ferry service since 1968. The SR N4 weighs 150 metric tons, cruises at 65 knots, and can carry 250 passengers and 30 cars. A 225 metric ton ACV transporter (nonself-propelled) for carrying oil field equipment is now operational in the Arctic; a 27 000 metric ton transporter for a similar purpose is nearing the construction stage. ACVs of 1000-2000 metric tons would be large enough to effectively use a nuclear powerplant.

Conceptual designs and the economic potential of large multi-thousand ton nuclear ACVs are described in Refs. 11 and 33 to 35. An artist's rendering of a conceptual nuclear-powered ACV freighter (4500 metric tons) is shown in Fig. 5. Such nuclear ACV freighters could have a flat-bed design that would permit them to carry containers, vehicles, and even modular housing as cargo (fig. 6).

Missions and implications of large ACVs have been discussed in Refs. 11, 27, 28 and 35 to 41. Two particular implications of ACV freighters are described below because they seem sufficiently important and far-reaching to stimulate the development of large ACVs, the growth of a large ACV industry, and the demand for a lightweight airborne MNP.

For nearly 500 years seafaring nations of the North Atlantic have searched for a Northwest Passage between the Atlantic and Pacific Oceans. Nuclear powered ACV freighters could open a Northwest Passage (through the Canadian Arctic Islands) or other Arctic passages across the North Polar Cap to commercial traffic in the time period 1985-2000 (ref. 28). As described in Ref. 28, a nuclear powered ACV freighter could provide (1) a shorter trade route between most of the major industrial and population centers of the world, (2) competitive cost with conventional displacement ships for containerized and roll/on/roll off cargo, (3) independence from the Panama and Suez Canals, and (4) all season, Arctic-wide mobility.

The mobility of the large ACV would not only permit new transportation routes but it would also provide a totally new geographic freedom in locating ports and laying out a port city (ref. 27) (fig. 7). By the 1980's fleets of large ACV freighters could begin to carry ocean-going cargo. The mobility of an ACV fleet would allow hoverports to be located away from present crowded areas. Such hoverports would provide new transportation nodes and thus could support new business, industrial and population centers. New cities could arise along shallow or reef-bound seacoasts and rivers just as cities once arose around deep water seaports.

There are already many reasons why new cities should be built. The large ACV and hoverport offer economic incentives for building them: competitive operating costs of ACV freighters, use of cheap land requiring little preparation, early economic strength as a trade center and creation of new jobs.

ACVs of 1800 metric tons gross weight and a speed of 100 knots would require a reactor power about 460 MWt (ref. 22). ACVs of about 9000 metric tons would require 2300 MWt for a 100 knot speed (ref. 22) and about 900 MWt for a 60 knot speed (ref. 41).

Airships

Airships could provide a versatile means of carrying cargo, independent of existing transport systems. Airships would not add to surface traffic congestion; they would require no specially prepared routes and only simple cargo transfer facilities. At virtually any location desired they could stand still in midair and, without actually landing, trans-

fer cargo between the airships and the ground. Airships could carry cargo to inland areas that have no roads, railways, airfields and are too rough to be accessible by ACV. One Soviet project plans to use airships to carry machinery to remote spots in Siberia.

As part of a revival in interest in airships a new West German dirigible recently began service for a European sky-advertising company and there are orders for more (ref. 42). Although the use and performance of the airship may be limited by the weather, its prospects for low cost are especially attractive. Hence, the use of dirigibles for advertising is only a first step. The builder of the small advertising dirigible (198 feet long, 62 mph, 1.5 metric ton payload) expects to begin building (in 1974) larger cargo airships (396 feet long, 87 mph, 30 metric ton payload). Their cost would be a little over \$1.5 million compared to \$25 million for an aircraft of the same payload and, of course, much higher speed. Even several airships, to provide the same productivity, would cost less than half of a single aircraft.

In England, Cargo Airships, Ltd. has been formed by the Manchester Liners Group of Companies to actively explore a transport concept (by M. J. Rynish) called the Merchant Airship Cargo Satellite System. Rynish envisions a system of 100-knot cargo airships, continually orbiting the earth at low level, relaying world trade in much the same way communications satellites are now relaying the world's messages (ref. 43).

Another reason airships have enjoyed a revival in interest in an energy-conscious society is their low power need. Thus, the usual advantages of a nuclear powerplant for higher power levels are not the "selling point" here. The features of MNPs that are useful are the low fuel volume and the constant weight throughout a mission. If chemical powerplants are used for long range, an appreciable space will be occupied by fuel. And as the chemical fuel is used up, the airship will become lighter and thus it must continuously adjust its ballast.

In the U. S. at Boston University, Morse has designed a conceptual nuclear airship (ref. 44). The advantages of using such a nuclear airship for oceanographic work have been described in Ref. 45.

The power needed for a nuclear airship would be about 6000 shp for an 85 knot, 80 metric ton payload, 340 metric ton lift capability (ref. 44). The reactor power would have to be about 18 MWt. A conceptual airship, the Europa (ref. 46), that would have the same productivity as the Boeing 747F would require 16 100 hp (a reactor power of about 40 MWt).

Aircraft

What nuclear aircraft potentially offer in a civilian capacity are almost unlimited endurance for inflight experiments and scientific observations (ref. 47), nonstop flights between any two airports on earth, and very low cost for fast cargo transport (ref. 23). With low cost cargo hauling costs and unlimited range, nuclear aircraft freighters would permit inland cities (such as Denver or Geneva, Switzerland) to become international ports. Inland cities could become as important in international trade as coastal seaport cities are now.

The large aircraft of today (the Lockheed C5A and Boeing 747) weigh about 380 tons; growth versions of these aircraft will approach 500 metric tons; and the next generation of large aircraft may approach 1000 metric tons. These coming aircraft will be large enough to accommodate a nuclear powerplant. In fact, in their present size, the C5A and the 747 could accommodate a high-power density (13.5 MW/ft^3) reactor (ref. 12). The Boeing Company has considered a conceptual aircraft to be used for resource transport, particularly oil (ref. 48). This vehicle would have a gross weight of 1600 metric tons, a payload of 1050 metric tons, a speed of 400 knots, and would be powered by twelve 50 000 hp engines. This resource transport vehicle considers only chemical fuel but the conditions of large size, high power needs, and the need for high utilization make a nuclear powerplant (with its long time between refuelings) an attractive alternative.

Conceptual studies of a nuclear powered airplane have been described in Refs. 10, 12, 13, 17 and 49. A nuclear powered C5A would require 200 MWt (ref. 12). From Ref. 23 the power required for a subsonic aircraft ranges from about 800 MWt for a 907 metric tons gross weight to about 2700 MWt for 3630 metric tons gross weight.

A bulk oil carrier of 1600 metric tons (ref. 48) would need a reactor of about 2000 MWt.

Resource Development

In addition to the growth of international cargo transportation, another situation has arisen in the past two decades that could be effectively served by mobile nuclear powerplants. The world now faces a dilemma of resource depletion versus increasing population and increasing per capita resource consumption. What really compounds this dilemma is that mineral consumption increases 2 to 3 times as fast as the population increases and energy consumption increases 4 to 5 times as fast as the population increases (fig. 8, taken from ref. 50). Furthermore, projections of these conditions indicate that the seriousness of this dilemma will not only increase but will do so at an even faster rate than in the past. Perhaps the most obvious, easily implemented, and hence likely-to-be-used way to ease this dilemma (at least temporarily) is to increase our discovery and extraction of raw materials.

Systems (vehicles, habitats, and machines) have been proposed and some demonstrated on a small scale that would allow man to open vast new regions of the earth for exploration and extraction of resources including the oceans and the Arctic. Efficient, economic, large-scale operations in these relatively remote and hostile environments may especially require the energy autonomy and endurance offered by nuclear powerplants.

The Oceans

The potential development of the oceans' resources has been discussed in many references (for example, see 50-60). The resources of interest in this report may be categorized as Minerals and Food.

Minerals - The minerals of the sea occur in several forms. Some of them are in concentrated form but are not renewable. For example, deposits of fossil fuels, sulfur, iron ore, and potash beneath the ocean floor are limited in the same way that land deposits are - the minerals were formed and deposited in ancient times and are nonrenewable.

But the oceans contain many minerals that are renewable. From Ref. 52: "Taking minerals from the land is like living on one's savings. But mining the ocean is living on income. Every stream and river reaching the sea carries with it dissolved minerals. Some of these are leached from rocks or soil. Some come secondhand from man. Metals corroding in junk yards, fertilizers spread on farm land, (and industrial and residential wastes) are converted to other forms through the action of wind, rain, and chemical change. One way or another the mineral wealth of the land gradually migrates to the sea." What is particularly important is that many of the minerals that could be taken from the sea are renewable, making the sea an "inexhaustible mine" (ref. 52).

However, many of these renewable minerals remain dissolved in the sea water. Sea water may be thought of as a diluted, very low grade "ore" for minerals (excepting of course, fresh water, hydrogen, oxygen and perhaps salt). However, the ease of handling large quantities of water relative to handling solid ores should mitigate the fact that the minerals are diluted (ref. 52). But because the dissolved minerals occur relatively uniformly in the seas, their extraction from the sea will probably be performed largely by land-based seaside plants which could have the large water flow capacity without much penalty.

Still other ocean minerals, however, are continuously concentrated in a variety of locations by a variety of processes. Examples are: sand, gravels, and oyster shells on continental shelves as a result of wave action; heavy metals in beaches, river mouths, and stream beds (for example, the Malayan offshore time deposits and the Japanese magnetite sands) also a result of wave action; nodules of manganese, phosphate, and nickel on the sea floor as a result of direct precipitation from sea water; calcium carbonate and silicon dioxide in sea floor oozes (the muck that is on the sea floor) composed of the remains of plants and animals such as diatoms, sponges, and corals; rich mineral salts in hot water basins in the Red Sea floor; and mineral concentrations in marine organisms (iron in some snails' tongues, iodine in sponges and seaweed, vanadium in tunicates and sea cucumbers, and copper, zinc, and lead in other creatures).

The point to be made here is the great variety of potential tasks associated with the development or extraction of these concentrated minerals that could require high-energy, high-endurance underwater instruments and powerplants: data collecting for research on concentration processes, prospecting (including exploring, mapping, sampling, and assaying), sea floor drilling and excavation, and collection and transportation of the minerals.

Presently, nearly all the work associated with sea resources is carried out from surface ships or from platforms in relatively shallow water. On the continental shelves and slopes and on the deep sea floor specialized surface ships are used extensively for exploration and mining. The ships used for mining employ the dredge techniques of bucket ladder, grab bucket, dragline, or suction (air-lift), all controlled from the surface ship. Needless to say, dredging from the surface has its drawbacks, especially in deep water or bad weather.

Hence, to explore and develop the mineral (and food) resources of the oceans, new submersibles of varying size, power, and depth capability will be needed.

For many localized tasks on the shelves and slopes, such as construction, digging, drilling, a tracked vehicle operating on the sea bed will be useful. One such manned sea-bed crawler, the Sealbeaver, has been built for use in the North Sea but is now mothballed because of company financial problems (ref. 61). The Sealbeaver's ability to withstand strong currents, avoid surface waves, provide a refuge for divers make it an ideal vehicle for work in the North Sea offshore operations. However, the Sealbeaver is confined to one end of an umbilical from a parent surface tender and hence can only operate when the tender is able to withstand the North Sea conditions. Nuclear power for sea bed crawlers would offer autonomous power and life support and therefore independence from surface support.

Sea-bed crawlers would also permit dredge techniques to be controlled from the sea floor (ref. 50). This would allow more selective excavation and collection of ores in contrast to dredge techniques controlled from the water surface. Other underwater ore collection and transportation to the surface might be performed by conveyors and air-or water-lift shafts.

Completely submerged shaft mining will require powers of 1 to 4 MWt for depths less than 300 meters (ref. 62). Between 300 and 7000 meters the power needed will be 4 to 350 MWt (refs. 54 and 62). For underwater oil wells and pumping stations, a gathering center and wellhead equipment along with pumps and storage will require 2 to 7 MWt (ref. 54).

However, the mobility required for exploration, prospecting, and research throughout the ocean volume and over the entire sea floor will require submarines. Submarines for research might be the largest submersibles needed, excluding commercial cargo submarines. They must be large enough to accomodate scientists and their instruments and will require extra power for the instruments and experiments and endurance for prolonged sampling and experiments. "Nuclear power will inevitably send research craft along the axes of the great submarine trenches and the flanks of the midocean ridges. The potential is too great to ignore" (Seaborg, ref. 53).

From Ref. 63: "What is lacking in our arsenal of ocean research and surveying platforms is an all-weather, all-ocean capability. . . for real advancement in ocean science, we must escape the air/sea interface with its problems and operate within the volume of the ocean. Ocean science needs a nuclear-powered research submarine to take us there. . . A nuclear submarine would be ideal for the following reasons: (1) Submergence into the ocean volume would allow research undisturbed by wind and waves. It would allow study of the marginal sea ice zones and the under ice regions of the world ocean. . . It would permit study of the birth and growth of hurricanes. . . For decades our ocean research has been biased toward measurements in temperate latitudes and seasons. . . (2) "On-station" time would be limited only by the endurance of the crew. . . After two decades of descriptive oceanography, we are ready for long-period time series and sophisticated experiments in the deep ocean."

One nuclear powered civilian submarine has already been built. The NR-1, launched in 1969 for undersea scientific and rescue missions, is about 50 meters long and weighs about 360 metric tons. From Ref. 53, J. Madell of Argonne has reported the design of a 7.75 MWt pressurized water reactor that would supply 2000 shp to drive a 30-meter oceanographic research submarine.

Reactors of 0.3 MWt to 8 MWt will be needed for research submarines (refs. 53, 54). Smaller submarines for prospecting, surveying, mapping, or search missions may require reactors of 100 to 400 kWt (ref. 54). Still smaller submarines, with one or two men, could have a variety of duties. These minisubs or underwater "work boats" could be used for localized exploration, mining, salvage, construction, or rescue. They would have manipulators, external power tools, television cameras, lighting and sampling systems. Their power needs would range from 50-200 kWt (refs. 54 and 62).

Food - We still hunt the oceans - which provide about 90 percent of the worlds animal protein - instead of ranching or farming them (from J. E. Karth, as cited in ref. 54).

Marine plants and animals could provide human food, fish meal for livestock food, fertilizers, and chemicals. Biochemical studies of marine life may lead to new insecticides, herbicides, soil conditioners, fertilizers, pharmaceuticals including antibiotics.

Small submersibles will be needed for stalking, tracking, and observing ocean fish and mammals so that man may learn to breed, feed, protect, and harvest desirable species for his needs. Later submersibles will be needed for ranching and roundup. Deep water submersible trawlers may be used for harvesting tuna, hake, anchovy, squid (ref. 54). Ocean shelf farming of oysters, scallops, lobster, shrimp, crab, abalone, eel and various kelp species will require sea floor harvesters and other marine farming equipment analogous to land farming equipment and perhaps processing equipment. Direct harvesting of algae and plankton will require pumps and processing equipment (ref. 54). Small submersibles for underwater farming and ranching will require powers of 50-100 kWt (ref. 62).

The abundant energy offered by nuclear powerplants could also be used for fish ranching by generating underwater electric fields to guide and contain fish herds, to attract, repel, or stun fish. The use of electric pulses instead of steady currents would reduce the power needed from thousands of kilowatts to hundreds or even tens of kilowatts (ref. 52). Electric currents of several thousand amperers would still be needed.

Furthermore, the reactor waste heat could be used to cause the thermal upwelling of bottom sediments and nutrients to the upper sun-lighted layers. This process might substantially increase plankton production, thus aiding fish growth in the current that surrounds the submerged heat source (ref. 54).

An additional role for surface marine nuclear powerplants may be for food (fish) preservation (refs. 52 and 72). Example: Although there are rich fishing grounds off the Thailand coast many of the Thai people are undernourished. As in all hot countries the rate of spoilage of fish is appalling. Even though fishing boats take just a few hours to get to shore the spoilage is considerable. For various reasons neither ice, nor canning, nor refrigeration and freezing are solutions (ref. 52).

However, a "factory ship" centrally located in a fishing area with on-board capability to irradiate the fish would offer preservation which would be insensitive to subsequent delays in distribution and consumption of the fish in any climate.

The Arctic

The Arctic is now being recognized as an abundant source of many raw materials. Oil has been discovered at Prudhoe Bay, Alaska, the MacKenzie River Delta, and Ellesmere Island, Canada. The Canadian Arctic Islands have been estimated to overlie a greater oil deposit than the Middle East (ref. 25). Near Mary River, a town in the northern part of Baffin Island, lies the largest and richest iron ore deposit in North America (ref. 64).

Nuclear-powered icebreakers (such as the Soviet N.S. Lenin) and drilling vessels (for offshore Arctic oil wells) would permit sustained, unsupported operation in the Arctic. Nuclear submarines for transport of Arctic oil and minerals were discussed earlier in this report.

The possibility of using ACVs configured as tankers to carry oil over the polar ice from the North Slope of Alaska around Point Barrow and south to be transshipped to a displacement tanker waiting in ice-free water has been described in Ref. 41. Large ACV tankers will not likely

compete economically with oil tanker or bulk ore carriers on open sea routes from present oil sources. But from Arctic sources they may. ACVs, with their potential Arctic-wide, year-round mobility, could provide an economical means of moving raw materials from remote ice-bound mines and wells to ice-free ports where the cargo could be trans-shipped to conventional displacement tankers, bulk carriers or pipelines.

The presence of vast mineral and fuel resources in the Arctic plus its potential (using ACV freighters) as a trade route between ports of the North Pacific and North Atlantic Oceans may be the prelude to settlement and development of the Arctic. The nuclear ACV would provide the heavy duty autonomous transportation needed to develop and operate in this remote and hostile region.

Remote Power Supplies

In the context that follows, remote refers to any location where an autonomous (and in this case, high energy) power supply is needed. Such power supplies might be used for stations or settlements, emergency power for disaster areas, or tunneling.

Two types of remote stations might require a nuclear reactor power-plant. One type, which includes underwater habitats and Arctic bases, requires large amounts of energy for life support and man-oriented systems. The other type is simply an energy depot - essentially a small, remote central power station.

Habitats

If we are to develop sea farming then we will need the equivalent of the land farmers' agricultural experiment stations (ref. 52). Many such aquaculture (or mariculture) experiment stations would need to be underwater. In addition to this type of habitat, other underwater habitats would be needed for farming or ranching villages, prospecting or scientific laboratories, or mining, drilling, or pumping stations. Habitat power will be needed for tools, instruments, lighting (inside and out), television

cameras and receivers, heating, air conditioning, and hydrogen-oxygen separation to provide breathing atmosphere. For simple manned work platforms or single small habitats the power level would range from 100-500 kWt (refs. 54, 62, 65). For more sophisticated or larger habitats or groups of habitats the power level would range from 1-10 MWt (ref. 54).

Much of the experience with mobile or portable nuclear powerplants has come from U.S. military use for remote settlements. Those reactors that have not been used for propulsion have ranged in power from about 500 kWt to 30 MWt and have been used to supply base power and heat in Greenland and Antarctica for example (fig. 9) (ref. 66).

An example from the Soviet Union illustrates several other advantages of nuclear powerplants for these applications (ref. 67). Several reactors will be used for each of several electric power stations that will serve mining operations in Siberia. Each station will be equivalent to 50 000 tons of coal and will provide heat and electricity for a settlement of 3000-5000 people and as well as providing heat for the mines. Present electric power stations in the Northern Soviet Union run on diesel oil and coal which must be transported during the brief summer months at a cost of about \$168 per ton of coal.

Energy Depot

The idea of a land-based mobile energy depot has been discussed in Ref. 66. One use for such an energy depot would be for local chemical fuel production. Presently, chemical fuel is transported worldwide over long supply lines from its natural source ultimately to a location where it is used. By using local constituents and the energy from mobile nuclear reactors, chemical fuel such as hydrogen or ammonia could be produced where it is consumed.

Underwater many small stationary and mobile systems (pumps, tools, excavators, harvesters, sea-bed crawlers, and minisubs) will not need enough power to justify individual nuclear powerplants for each. A reactor serving as a small central power station could supply electricity by cable, provide an energy service for recharging battery-driven instruments,

produce chemical fuel such as hydrogen, or produce hydrogen and oxygen for fuel cells.

A mobile energy depot could also be quite useful in situations where normal power is disrupted for a prolonged period or where power is needed for a temporary project. One example is emergency power for disaster areas; mobile power supplies might be carried by ship to coastal sites, such as the MH 1A on-board the U. S. S. Sturgis could be.

In another example of the versatility of the ACV, it could carry power to sites on shallow coasts, up rivers, and even inland for some distance. In fact, the ACV can become a self-propelled power source with unusual mobility. Instead of carrying cargo the ACV would carry energy in immediately usable form (heat, electricity, or turbine steam)).

Let's go one step further. And it is really not a big step because in 1967 one could already buy from the British Hovercraft Corporation an ACV Medical Center completely equipped with operating table and dental chair. A large ACV with a flatbed design could have a deck space of half an acre or more; it ought not to be difficult to configure the ACV as an integrated mobile base (fig. 10). With a nuclear powerplant an entire base consisting of barracks, research and recreation buildings, medical clinic, and equipment and base service center could be mounted on an ACV. This mobile base would be capable of operating while moving or serving as a stationary base temporarily or for extended periods of time (several years) until the craft would have to return for refueling.

Tunneling

On land the energy requirements for tunneling offer a possible application for MNPs. New ground transportation in metropolitan areas will require extensive tunneling because of aesthetics, safety and economic and social problems in removing existing above-ground structures. Unfortunately the present construction costs of tunnels and underground terminals is high, so that new, cheaper tunneling methods are needed.

One new, experimental method of tunneling is by thermal disintegration, raising the temperature of the rock so high that it breaks by differ-

ential expansion or that it melts (ref. 68). Lasers are being investigated as one approach (refs. 69-70) by using them to heat-weaken or score the rock face ahead of the cutter blades on the boring machine. Although it is too early to know how much of the rock face must be heat-weakened or what the specific energy for weakening is or how much must be scored, estimates are that for a 6 meter diameter tunnel a 0.5-1 MWt laser will be needed (refs. 68-69). For a thermal to electrical conversion efficiency of 30 percent and an electrical to laser conversion efficiency of 50 percent (ref. 71) a reactor would need 3.5-7 MWt.

SUMMARY OF POWER NEEDS

This section merely collects and arranges by power level the applications previously discussed (table II). Most of the reactor powers listed are approximate. For some applications a range of power is given, for others only a single power level is appropriate or could be found.

Table III lists the systems that may require MNPs and the range of power that may be needed for varying sizes and capabilities.

CONCLUDING REMARKS

Various consequences of increasing population and per capita resource consumption indicate a need for MNPs.

The growth in volume of world trade, which is expected to continue, has made larger and faster cargo vehicles economically attractive. These vehicles require more power and as the power required increases nuclear power becomes more competitive.

Depletion of known fuel and mineral deposits requires discovery and development of new deposits, an increasing number of which will likely be in previously remote regions, for example, the oceans and the Arctic. New systems (vehicles, habitats, and machines) will be required for these tasks. At first these systems can be chemically fueled. But as the new capabilities become more necessary and require more energy the utility of the systems using chemical fuel may then be improved markedly through the use of mobile nuclear powerplants.

Because fossil fuels are nonrenewable and are being rapidly depleted, it is becoming increasingly important that we reduce our dependence on them. The widespread use of nuclear fuel in marine transport alone could substantially ease the demand for our diminishing supply of petroleum.

Many factors will shape the development and use of MNPs - need, economic feasibility, social acceptance, and technical feasibility of MNPs and the systems that will use them. One application, with exciting and prolific possibilities for its use, is the air cushion vehicle.

This examination of the potential applications for MNPs can serve three major purposes: (1) to identify the broad range of socially-derived needs toward which MNP research and development could apply, (2) to identify the potential importance of an advanced powerplant technology in terms of capability and diversity of application, and (3) to become a key part of any later assessment of the total impact of this technology.

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TABLE I. - EQUIVALENT TANKER FLEETS
(FROM REF. 2)

Example	Fossil steam propulsion	Nuclear steam propulsion
Number of ships	8	5
Speed, knots	15.5	24
shp, each	35 000	120 000
dwt, each	250 000	250 000
Percent fuel volume	2-6	0
Annual fuel costs, millions \$	10-12	5-6

TABLE II. - MOBILE NUCLEAR POWERPLANT APPLICATIONS

Application	Description ^a	Reactor Power Requirements (megawatts thermal)	References
Underwater work boat	small, 1-2 man submersibles	0.05-0.075	58
Exploration sub	deep submergence vehicles	0.15-0.35	19
Single habitat	underwater work platforms	0.15-0.35	19, 60
Mining conveyor	depth to 300 m	0.5-3.5	58
Large habitat	living quarters, energy depot	1.5	19
Habitat village	groups of habitats	1.5-7	19
Oil well	gathering and pumping stations	1.5-7	19
Laser tunneler	6 m diameter	3.5-7	61, 62
PM-3A	base power, McMurdo Sound	5	6
Research Sub	deep submergence, 30 m long	8	5
Large base	remote settlements (Arctic)	0.5-30	6
Shaft mining	water or air lift (deeper than 300 m)	15	19
Airship	380 mtg, 90 mA, 85 kt	20	51, 52
MH-1A	installed on Sturgis	30	6
Mutsu	research ship, 16.5 kt	36	26
Otto Hahn	ore carrier, 15 000 dwt; 15 kt	38	26
Airship "Europa"	conceptual, 630 mtg, 270 mt, 108 kt	40	53
Savannah	9500 dwt, 21 kt	74	26
Enrico Fermi		80	26
Cargo sub	40 000 mtg, 20 kt	70-100	33
Container ship	20 000 dwt, 24 kt	80-100	28
Supertanker	250 000 dwt, 16 kt	90	26
Mining	water or air lift (>300 m)	100-350	5
Cargo sub	50 000 mtg, 22 kt	100	33
Supertanker	400-500 000 dwt, 16-18 kt	150-250	26
CSA	350 mtg, 13.5 MW/ft ³	200	54
Submarine	170 000 dwt, 19 kt;	250	31
tanker	250 000 dwt, 17 kt		
Container ship	40 000 dwt, 33 kt	300	1
Supertanker	250 000 dwt, 24 kt	300	1
ACV	1800 mtg; 900 mt; 100 kt; 3 MW/ft ³	460	29
Cargo sub	100 000 mtg; 37 kt	550	33
Aircraft	900 mtg; 150 mt; 400 kt, 3 MW/ft ³	800	30
ACV	3600 mtg; 2000 mt; 100 kt, 3 MW/ft ³	900	29
ACV	9000 mtg; 5400 mt; 60 kt; 3MW/ft ³	900	4
Aircraft	Boeing Resource Transporter 1600 mtg; 1050 mt; 400 kt, 3 MW/ft ³	2000	55
ACV	9000 mtg; 5400 mt, 100 kt	2300	29
Aircraft	3600 mtg; 1100 mt, 400 kt	2700	30

^a Payload for ships is in deadweight (long) tons (dwt)
 Payload for air vehicles is in metric tons (mt)
 Gross weight or displacement is in metric tons (mtg)
 Cruising speed is in knots (kt)

**TABLE III. - SYSTEMS AND THEIR
POWER NEEDS**

Instrument	Reactor power level (megawatts thermal)
Submersible	0.05 - 10
Habitat(s)	0.10 - 30
Energy depot	
Mining machines	0.5 - 400
Tunneling machines	3 - 50
Airship	20 - 40
Existing ship	36 - 80
Future merchant ship	80 - 300
Cargo submarine	70 - 600
Air cushion vehicle	200 - 2500
Aircraft	200 - 3000

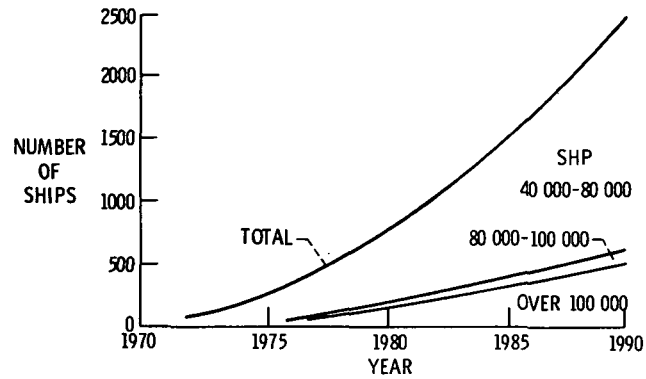


Figure 1. - Projected worldwide requirement for high powered ships (power about 40 000 SHP) (from ref. 2).

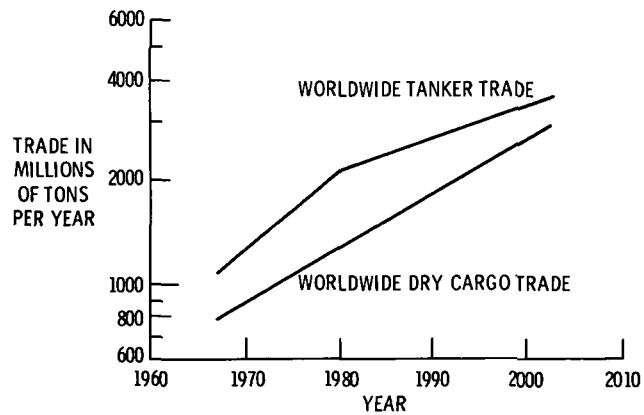


Figure 2. - Worldwide trade forecast (from ref. 2).

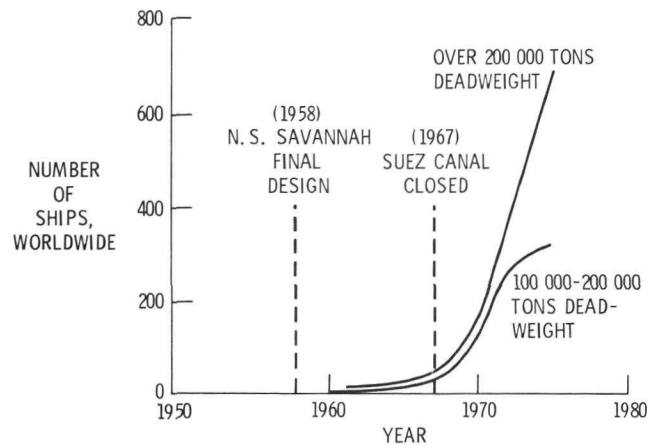
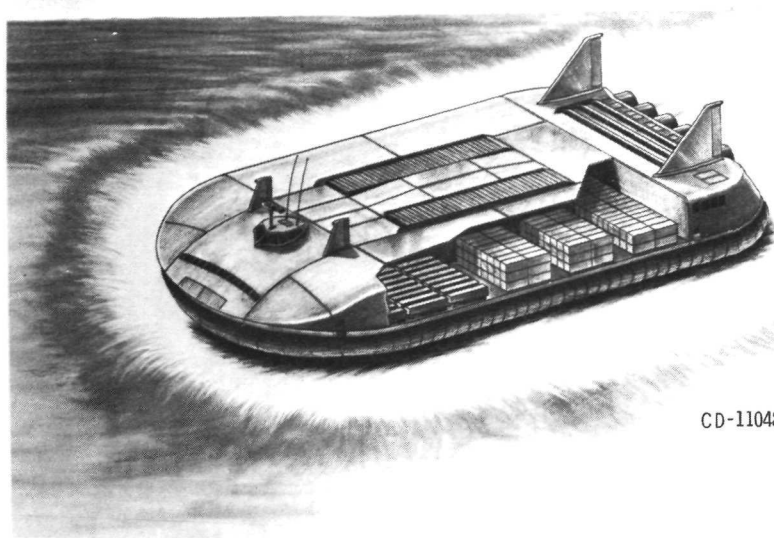


Figure 3. - Growth of dry bulk carriers (from ref. 2).

BRITISH HOVERCRAFT LTD. SRN-4 AIR CUSHION VEHICLE

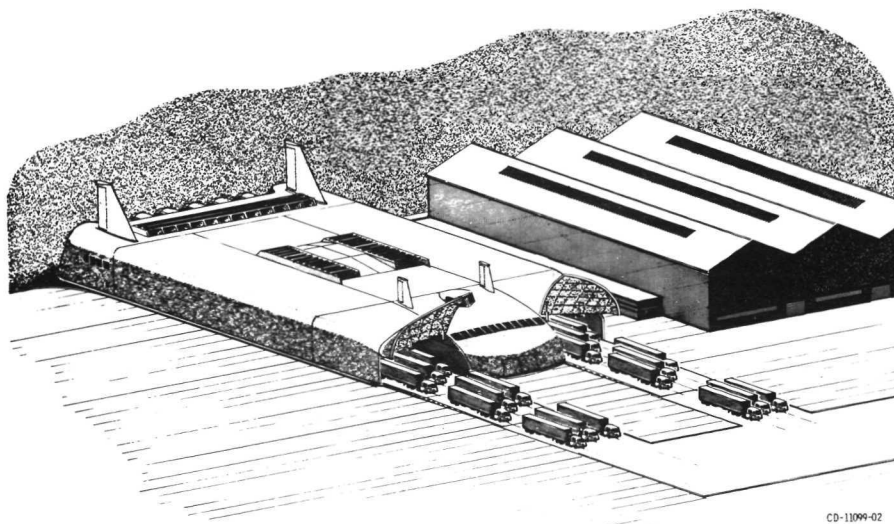


Figure 4.



CD-11048-22

Figure 5. - 4500 metric ton nuclear ACV freighter.



CD-11099-02

Figure 6. - ACV freighter in roll off cargo transfer mode.

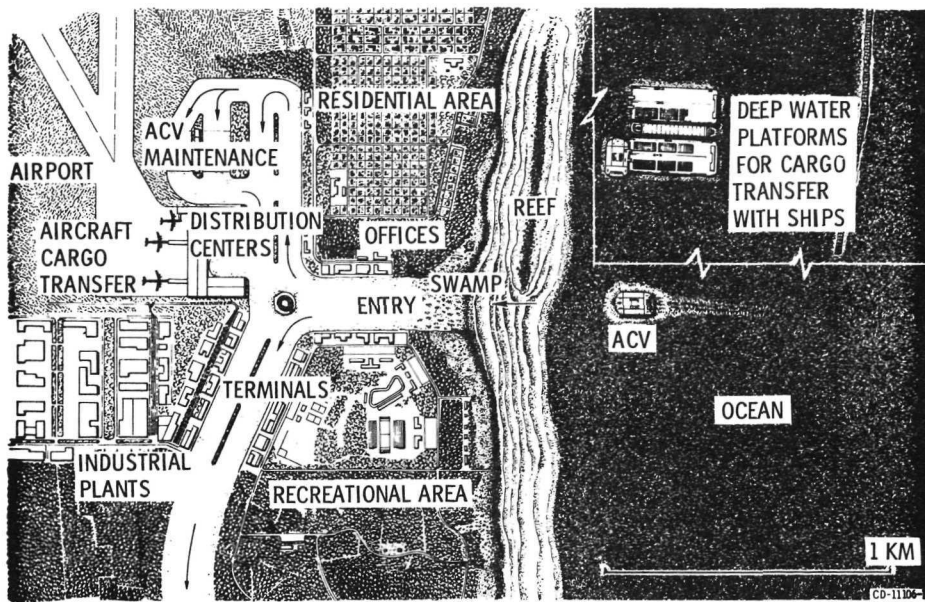


Figure 7. - City-port for nuclear ACV freighters.

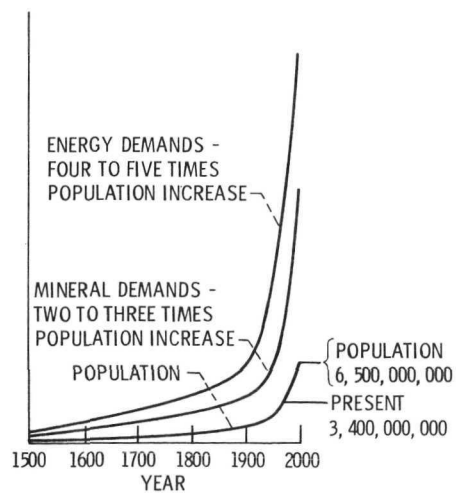


Figure 8. - Projection of population and mineral and energy demands (from ref. 50).

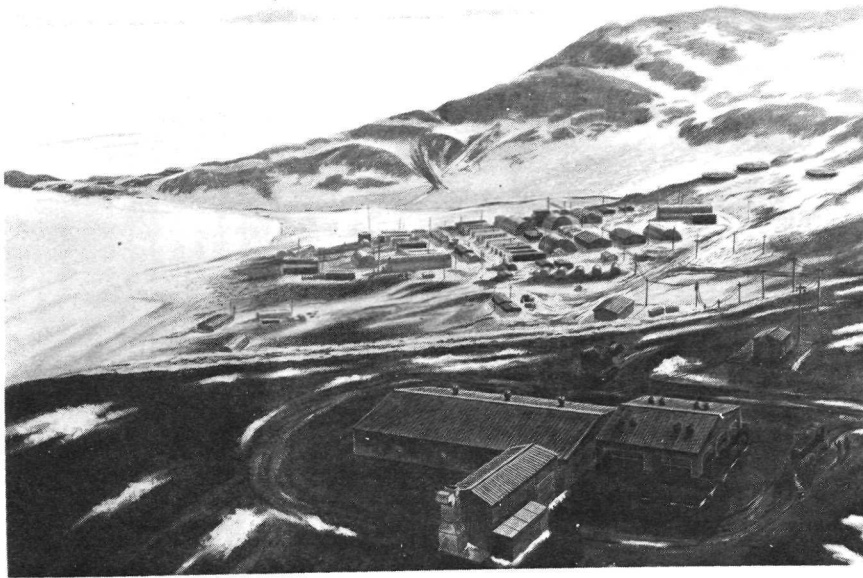


Figure 9. - PM-3A nuclear power plant installation, McMurdo Sound, Antarctica.

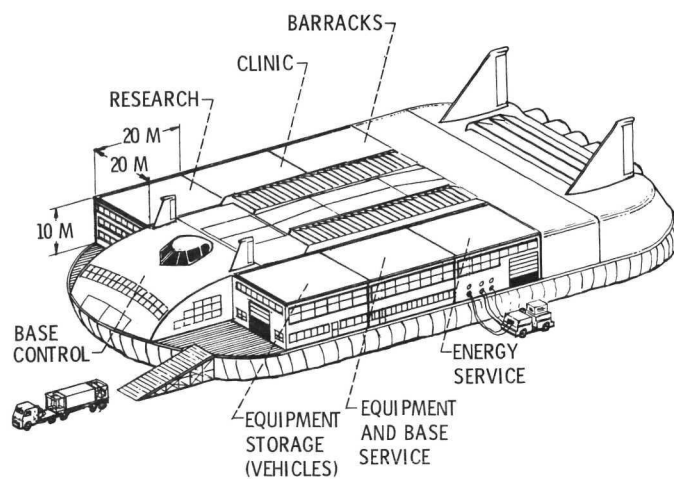


Figure 10. - Large ACV as an integrated mobile base. (Reactor provides both propulsion/lift and base power.)